# Safety in Domestic Robotics : A Survey

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***Abstract*—Different branches of technology are striving to come up with new advancements that will enhance civilization and ultimately improve the way of life. In the robotics community, a stride has been made to bring the use of personal robots in office and home environments on the horizon. Safety is one of the critical issues that must be guaranteed for successful acceptance, deployment and utilization of domestic robots. Unlike the barrier based operational safety guarantee that is widely used in industrial robotics, safety in domestic robotics deals with a number of issues such as intrinsic safety, collision avoidance, human detection and advanced control techniques. In the last decade, a number of researchers have presented their works that highlighted the issue of safety in a specific part of the complete domestic robotics system. This paper presents a general survey of various safety related publications that focus on safety criteria & metrics, mechanical design & actuation and controller design.**

## I. Introduction

Recent advances in robotics led to the growth of robotic application domains such as medical [1], [2], [3], military, rescue [4], [5], [6], personal care [7], [8], [9], [10] and entertainment [11], [12]. Out of these categories, a personal care robot is defined as “a service robot with the purpose of either aiding or performing actions that contribute towards improvement of the quality of life of an individual” [13]. A domestic robot is a personal care robot with or without manipulators that operates in home environments, and is often mobile. This cohabitation of domestic robots and a human in the same environment raised the issue of safety among standardization bodies [14], [13], research communities [15], [16], [17], [18] as well as robot manufacturers [19], [20], [21], [22].

As an attribute of dependability, safety is one of the fundamental issues that should be assured for flourishing use of domestic robots in the future [23], [24]. In general, safety in domestic robotics is a broad topic that demands ensuring safety to the robot itself, to the environment and to the human user, with the latter considered the most important requirement. In a robotic system where human interaction is involved with a certain risk, it is important to do a careful robot design, taking into account the famous Murphy’s law: “If something can go wrong, it will”. Standard safety requirement used in robotics include a three step safety guideline: (1) risk assessment; (2) risk elimination and reduction; and (3) validation methods [14], [13], [25].

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The primary risk assessment step identifies a list of tasks, environmental conditions and potential hazards that should be considered during system design. Different techniques of performing risk assessment in order to identify and methodically analyze faults in robotic systems are presented by different authors [26], [27] as well as ISO 12100 standard [28]. The following risk identification and reduction step, by itself, is an iterative three step process that include safe design to avoid or minimize possible risks, a protection mechanism for risks which can not be avoided by design and finally a warning to the user in case both design and protection failed. The final validation step establishes methods that are used to verify whether desired safety requirements are satisfied by the developed system.

Even if all the three steps are equally important to design robots that can be used in human environments, most of the safety related works in domestic robotics over the past decade focused on risk elimination and validation steps in a selected part of the total robotic system. Hence, this survey left out works related with risk assessment and covers publications that include risk elimination and validation steps of the standard robotic safety requirement in domestic robotics. For a complex domestic robot which consists of different mechanical, sensing, actuation, control system, perception and motion planning subsystems, see Fig 1, analysing overall safety can be done by using the concept of functional safety [29], [30]. This systematic approach allows safety evaluation of domestic robots based on standardized functional safety of each subsystem as well as the interactions that exist between them. Typical functional safety standards that can be used for safety analysis are ISO 13849: “Safety of machinery: Safety related parts of control system” and IEC 61508: “Functional Safety of Electrical/Electronic/Programmable Electronic Safety-related Systems”.

This survey first presents different *safety metrics* that are used to validate safety of a domestic robot during unexpected collision between the robot and a human user. Then using a system based view of safety, the following sections discuss various safety enhancement ideas in *mechanical design & actuation* and *controller design* for domestic robots.

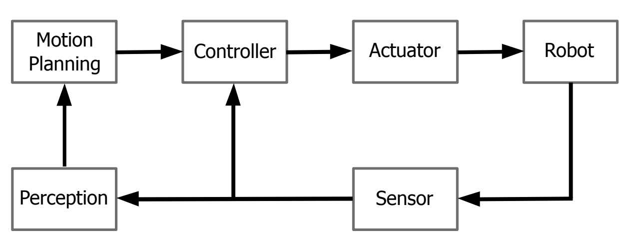



Fig. 1. Typical robotic system

## II. Safety Criteria and Metrics

Domestic robots require meaningful criteria and metrics in order to analyse safety and define injury levels of potential hazardous conditions. Safety criteria define desired design requirements while the quantitative safety metrics, defined based on the criteria, are essential for providing insightful safety improvement ideas, comparing successful system implementations and assisting system accreditation. Safety metrics are in general used to identify what injury a robot might cause [31]. The safety criteria are mostly part of an international standard that is acceptable by the manufacturing industry as well as the research community.

A standard framework used when dealing with safety in robotics is risk or injury based safety requirement which requires system level analysis of safety. The International Standard Organization (ISO) uses this approach to release a set of safety requirements for robots such as ISO 10218-1-"Safety requirements for robots in manufacturing industry". These standards are updated when needed and in the case of ISO 10218-1 a revised standard was released that deals with the emerging requirement in industrial robotics to share a workspace with humans [32]. An ISO committee has also addressed the issue of safety in personal robots and released an advanced draft of their work ISO 13482-"Safety requirements: Non-medical personal care robot" [33].

There are a number of hazards and risks which are included in the safety standard for domestic robots but contact based injuries can be divided into two types: quasi-static clamping and dynamical loading. Different subclasses of the injuries exist depending on the constraint on a human, singularity state of the robot and sharpness of the contact area [34]. The dynamic loading collision between a robot and a human can be either a blunt impact or a sharp edge contact in which possible injuries range from soft tissue contusions and bruises to more serious bodily harm. Collision analysis and modeling for investigation of injury measurement was presented in [35] while [36] discussed details of soft tissue injuries such as penetrations and stabs using experimental tests. There is no universally accepted safety metric that measures these injuries but a number of approaches have been presented. The common safety metrics used to measure collision and clamping risks in domestic robotics can be categorized into different groups based on the parameters they use as *acceleration based*, *force based*, *energy/power based* or *other parameter based*.

### A. Acceleration based

The most widely used safety metrics in domestic robotics for injuries due to collision is the acceleration based Head Injury Criteria (HIC) [37]. The metric is derived from human biomechanics data given in the Wayne State Tolerance Curve [38] and is used in biomechanics studies and accident researches in different fields such as the automotive industry. It is a measure of the head acceleration for an impact that lasts for a certain duration and is given mathematically as [39],

$$HIC_{\Delta t} = \Delta t \left[ \frac{1}{\Delta t} \int_0^{\Delta t} a(\tau) d\tau \right]^{2.5} \tag{1}$$

where $a(\tau)$ is the head acceleration normalized with respect to gravity $g$ and $\Delta t$ is measurement duration which is often taken as $15ms$ to investigate head concussion injuries [39].

HIC has been used in robotics as a severity indicator for potential injury due to blunt impacts to a human head. Such collisions typically exhibits a high frequency behaviour above the controller bandwidth and thus are mainly influenced by the link dynamics, and for stiff robots also by the motor dynamics. [40] used HIC based safety requirement to identify dynamic constraints on a robot and then used the constraint information obtained to define a performance metric that allows a better trade-off between performance and safety. The effect of different robot parameters on HIC is analyzed and experimentally verified in [34]. This insightful work included experimental results with different robots to conclude that a robot of any arbitrary mass can not severely hurt a human head if measured according to HIC because of the low operating speed. In a subsequent overview publication, the authors applied a number of safety criteria while investigating the safety of a manipulator at a standard crash-test facility [41]. The authors conducted a meticulous safety analysis of the manipulator based on human biomechanics and were able to present quantitative experimental results using different safety metrics for head, neck and chest areas. For unconstrained blunt impacts the authors used HIC as a metric for severe head injury. While reviewing different topics in physical human- robot interaction, [24] noted the need for a new type of safety index in robotics other than HIC because the type of injury and operation speed in robotics is different from that of the automotive industry where HIC is a standardized metric during crash tests.

Other metrics whose results are interpreted based on HIC were also reported in literature. [42] proposed a metric based on HIC known as Manipulator Safety Index (MSI) that is a function of the effective inertia of the manipulator. After identifying that safety of a manipulator is influenced mainly by the effective inertia of the robot, this index is used to compare effective inertia and hence safety of different manipulators under a constant impact velocity and interface stiffness. This metric was used to validate safety of a manipulator after design modifications in [43], [44]. [45] developed and investigated three danger indexes whose results were interpreted based on HIC. The work investigated force, distance and acceleration related danger indexes on a model to give quantitative measure of severity and likelihood of injury. The authors proposed a danger index that is a linear combination of the above qualities and takes into account speed, effective mass, stiffness and impact force.

### B. Force based

The other category of safety metrics for contact injuries is the force based criteria which considers that excessive force is the cause of potential injuries and thus should be limited. Covering detailed analysis on force based criteria, authors in [46] used minimum impact force that can cause injury as a factor to define a unitless danger index to quantify safety strategies. The danger index $\alpha$ of a robot is defined as

$$\alpha = \frac{F}{F_c} \tag{2}$$

where $F_c$ is the minimum critical force that can cause injury to a human and $F$ is the possible impact force of the robot. It was shown that quantifying safety using this extendable metric was used to achieve safer design and improved control strategy. In the mechanical design aspect the index was used to relate safety and design modifications such as low mass, soft covering, joint compliance and surface friction or a combination of them.

[47] proposed three safety requirements essential in human robot interaction: ensure human robot coexistence, understandable and predictable motion by the robot and no injuries to the user. The author then defined a safety metric called impact potential based on the maximum impact force that a multi DOF robotic manipulator might exert during collision. For a set of possible impact surfaces on the robot $P$, the impact potential is given as

$$\pi = \sup_{p \in P} \pi_p \tag{3}$$

,where $\pi_p$ is worst case impact forces at contact point $p$ on the surface of the robot.

Due to the low HIC values observed even for heavier robots as a result of low collision velocity, [48] proposed to use minimum forces that cause damages to different body parts as a safety metric. Since different body parts have different tolerance limits, the limit for neck injuries was chosen as a working criteria as it has the lowest value. A force based safety criteria was used by [49] to investigate safety of a pneumatic muscle actuated 2-DOF manipulator because HIC, according to the authors, does not provide an absolute measure of danger. While analyzing safety of a manipulator with respect to injuries at different parts of the body, [41] used maximum bending torque as neck injury metrics and verified safety for quasi-static constrained impacts at different body parts by using the maximum contact force as a metric whose allowed tolerance for different body parts is previously known.

### C. *Energy/power based*

Different emperical fits were being suggested for the Wayne State data other than HIC approximations and one of them proposes reducing the power in equation (1) to 2 [50]. According to this approximation, the equation then becomes

$$f = \frac{1}{\Delta t}\left[\int_0^{\Delta t} a(\tau)d\tau\right]^2 \tag{4}$$

$$f = \frac{\Delta V^2}{\Delta t} \tag{5}$$

where $\Delta V$ is the change in velocity of the head.

According to equation (5), possible injury to a human is proportional to the rate of kinetic energy transferred to the body during impact. Based on this observation, Newman et al. introduced a power based safety metric called Head Impact Power (HIP) from experimental investigations. By evaluating concussion injury due to an impact on a human head, the proposed HIP risk curve relates the probability of having concussion injury with amount of power transferred during collision. The rate of energy transfer was also suggested as a viscous criterion safety metric for constrained organs injury [51]. According to the viscous safety criterion, injury to human organs is proportional to the product of the compression and the rate of compression.

Uncontrolled extra energy was also suggested as cause of accidents in robots [52] and various experimental tests on the dynamic responses of human biomechanics during impact were performed to define energy based safety metrics that can be used in robotics. [53] and [54] identified energy limits that cause failure of cranial bone on adult and infant subjects respectively. The energy that causes a human skull fracture per volume of the skull was given as $\varepsilon_{adult} = 290KJ/m^3$ and $\varepsilon_{infant} = 160KJ/m^3$ for an adult and six month old infant respectively. The amount of energy that can cause fracture of neck bones and cause spinal injuries were determined in [55]. Accordingly, the amount of energy that can damage the spinal cord of an adult human was averaged at $E_{neck} = 35J$. It is apparent that, since the aforementioned energy based tolerance values are obtained from severe fracture injuries, they can not be directly used as acceptable safety threshold limits for domestic robots.

### D. *Other parameter based*

Other safety metrics proposed for use in domestic robotics are based on factors such as pain tolerance, maximum stress and energy density limit. The human pain tolerance limit for clamping or sudden collisions was used as a metric for safe robot design by [56]. The pain tolerance limit of a human at different parts of the body was used to identify the admissible force during normal operations and a soft covering of the robot was designed based on this value. Strong correlation between the pain felt by a human and impact energy density was indicated from experimental investigation on collision of a robotic manipulator with a human [57].

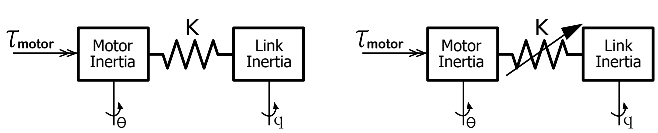
[58] focused on skin injury to a human and provided a safety metric that evaluates the safety of a robot design based on its cover shape and material covering. By using Hertzian contact models to represent the impact, the proposed safety norm identifies safe design choices by evaluating the maximum stress on the skin that will occur during impact of a point on the robotic cover against a human body. Focusing on soft tissue injuries, [59] also developed a Hertz contact theory based collision model between a covered robot and a human head to analyze laceration and contusion injuries. Then by using tensile stress and energy density limits of the skin as a safety criteria, the authors proposed allowable elastic modulus and thickness for a robot covering. Soft tissue injuries that might result from sharp edge contacts between robot operated tools and a human user were assessed using medical classifications in [60]. Instead of using using a safety metric to define the injury level observed, this experimental study defined a risk curve that directly relates the observed injury with the mass, velocity and geometry parameters of the operating robot.

## III. Mechanical Design and Actuation

Variations in use cases and in performance requirements between domestic and industrial robots understandably lead to different designs. Robots designed for industrial purposes have a high stiffness to achieve the main performance requirement, which is accuracy, and consist of heavier links to handle heavy loads [61]. Domestic robots are mostly designed with use cases that include performing human like activities in unstructured environments and hence have distinct mechanical design requirements [62], [63], [7].

Safety in mechanical design and actuation deals with the crucial issue of ensuring inherent safety, i.e., safety even in the unlikely case of loss of the entire control system. To achieve inherent safety, robotic arms mounted on domestic robots are designed to be lightweight and compliant so as to mitigate any possible injury that may arise in case of uncontrolled collision with human. The presence of compliant behavior in the manipulator might result in unwanted oscillations during motion and compromise system performance. Hence, advanced controllers should be used to compensate the performance degradation in flexible robots [64] and enable acceptable trade off between safety and performance [40]. The most widely used performance metric in mechanical design of robotic manipulators is the payload-to-weight ratio which is defined as the ratio of maximum payload that the robot can manipulate to its standalone weight. Mechanical designs in domestic robot manipulators are aimed at achieving a higher payload-to-weight ratio while being able to perform tasks defined in their use case [63], [43].

The main safety based design rationale behind the light weight links in domestic robotics is reducing the impact force by lowering the kinetic energy of the link. Compliance between the actuator and the end effector is essential to decouple the actuator inertia and the link inertia, so that only the inertia of the lightweight link is felt during uncontrolled impact. The dynamic relationship between the desired decoupling behaviour, the maximum impact force and the mechanical properties of flexible manipulators was recently investigated in [65]. [34] indicated that even a moderate compliance achieved by using harmonic drives was able to yield required decoupling and further lowering of compliance reduces impact torque at the joint, thereby protecting the robot itself during collision. The compliance can be implemented as either active compliance by using control [66], [67], [63], passive compliance by inserting elastic elements at the joint actuation [68] or a combination of both in one manipulator as used in [69]. Though active compliant manipulators offer satisfactory performance for nominal operation, current investigations in compliant actuation are trying to exploit the wide range of compliance and faster dynamic response rate offered by passive compliance [70], [68].




(a) (b)

Fig. 2. Schematics of (a) SEA and (b) VIA

The first approach to have a compliant robot, called Series Elastic Actuation (SEA), was done by inserting a passive compliant element between the joint and the actuator's gear train [71]. The authors presented a force controlled actuation with less danger to the environment and less reflected actuator inertia during impact. See Fig. 2(a). A modified SEA actuation approach, variable impedance actuation (VIA), allows tuning of the compliance in the transmission for improved performance and collision safety [72], [40], [35]. This mechanism allows for adapting the mechanical impedance depending on the tasks, to yield a wide range of manipulation capabilities by the robot. See Fig. 2(b). Various VIA designs have been proposed in literature, that differ in their range of motion and stiffness [73], [74], [75], [76]. Though the potential inherent safety of SEA and VIA comply with the prioritized risk reduction of mechanical design over control system as proposed in ISO 12100, the energy stored in the compliant element of VIA can lead to increased link speed and compromise safety as indicated in [77]. It should also be noted that, VIA design also incorporates damping of the compliant joints to avoid unnecessary vibrations during operation.

(a) (b)

Fig. 3. (a) DLR lightweight robot arm and hand [78] and (b) Stanford Safety Robot [43]

One of the earliest generation of manipulators designed for human interaction is the DLR lightweight robot with moderate joint compliance and suitable sensing and control capability [63]. See Fig. 3(a). The manipulator was planned to perform human arm like activities and mimicked the kinematics and sensing capability of a human arm. The manipulator has an active compliance, made possible by a joint torque control and was able to have a payload-to-weight ratio of approximately 1:2. New generations of the DLR lightweight robot included advanced control system [79] and achieved a payload-to-weight ration of 1:1 whilst safety for interaction is evaluated by using HIC [78]. A new DLR hand arm system was also developed with the aim of matching its human equivalent in size, performance and weight [80]. The design uses a number of variable stiffness actuation designs and exploits the energy storing capability of compliant joints to perform highly dynamic tasks.

Another actuation scheme designed to fit in the human friendly robotics is distributed macro-mini actuation (DM2). This novel actuation mechanism introduces two parallel actuators that handle the high and low frequency torque requirements [81]. In the first prototype that uses this mechanism, the low frequency task manipulation torque actuation was handled by a larger electrical actuator at the base of the arm while high frequency disturbance rejection actions were performed by low inertia motors at the joints. Compliance is provided by using low reduction cable transmissions for the high frequency actuation and series elastic actuation for the low frequency actuation. A continued research by the research group introduced Stanford Human Safety Robot, S2$\rho$, with the same distributed actuation concept but replaced the heavy electrical actuators with pneumatic muscles to have a hybrid actuation arm [43]. The authors reported an improved payload-to-weight ratio and control bandwidth while evaluating the safety requirements using Manipulator Safety Index (MSI). Further iterations on the S2$\rho$ were indicated to have an improved control, responsiveness and range of motion [44].

Another mechanical design relevant for safety of a robot is a passive gravity compensation shown in [82]. The mechanism which is common in machine design uses geometrical analysis and springs to balance the gravitational energy with a strain energy. Previously passive gravity compensation was made possible by using a counter mass that annuls the effect of gravity on the target manipulator. The spring based system has an advantage over the counter mass in that it avoids addition of inertia which is unnecessary in domestic robotics. An extended arm actuation mechanism that uses passive gravity compensation was presented in [7]. Together with a backdrivable transmission this design enhances safety and reduces the torque requirement at the joint actuators.

Though most of the discussion in this section focused on manipulators that can be used on autonomous domestic robots, the idea similarly applies to mechanical design of other robot parts such as trunk or mobile base. Aiming to emulate a natural reaction of human's waist to collision, authors in [83] designed a passive viscoelastic trunk with a passive movable base. Other mechanical design issues addresses with regards to safety include using a backdrivable transmission [84], eliminating pinch points by covering dangerous areas of the robot, analyzing flexibility of non-rigid links [24], adding force limiting devices [85] and placing a compliant cushion covering [56].

## IV. Controller Design

When it comes to controlling the robot to execute a planned motion and accomplish a task, most industrial robots use position controllers. This is because most robots perform position focused simple tasks such as spot welding,spray painting or pick and place operations in well known operating environment [86]. In tasks that demand contact with an object during operations, industrial robots adopt force control techniques to regulate the amount of force applied by the robot during the interaction [87]. Later, based on operational force and position constraints imposed on a manipulator, a hybrid position/force controller was introduced that uses position control on some degree of freedom and force control for others [88], [89], [90]. In general, pure position controller exhibits an infinite stiffness characteristic working in a zero stiffness environment while pure force controller exhibits a zero stiffness characteristic working on a stiff environment.

For domestic robots that often operate in human present unstructured environment, pure position control is incomplete because if there is a contact with an obstacle, the robot is not expected to go through the obstacle. Similarly a pure force control is also inadequate as contact-less tasks and motions are difficult to implement. An alternative control technique essential in domestic robotics is interaction control scheme, which deals with regulating the dynamic behaviour of the manipulator as it is interacting with the environment [91]. The core idea behind interaction control is that manipulation is done through energy exchange and that during the energetic interaction the robot and the environment influence each other in a bidirectional signal exchange. Thus by adjusting the dynamics of the robot, how it interacts with the environment during operation can be controlled.

One of the most widely used interaction control scheme is impedance control presented in [92]. Most operating environments of the robot such as mass to be moved or rigid obstacles in work space can be described as admittances which accept force inputs and output velocity during interaction. Hence for possible interactions in such environment, the manipulator should exhibit an impedance characteristic which can be regulated via impedance control. Consider a simplified 1-DOF robotic manipulator modeled as a mass $m$ at position $x$ which is to be moved to a desired position $x_d$, a simple physical controller that can achieve this is a spring connected between the desired virtual point and the mass. See Fig 4. To avoid continuous oscillation of the resulting mass-spring system and stabilize at equilibrium point a damper should be added to the system. The resulting controller is an impedance controller that can shape the dynamic behaviour of the system.

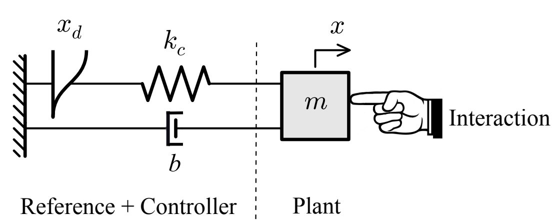



Fig. 4. Impedance controlled system

The controller resembles a conventional PD controller and introduced a desirable compliance to the system. A number of impedance controller designs have addressed issues such as robustness [93], [94], adding adaptive control techniques [95], [96], extension with learning approach [97], dynamics of flexible robot [79], [98], dexterous manipulation [99], [78], [100].

Another crucial requirement in controller design for domestic robots is ensuring asymptotic stability even at the presence of apparent uncertainties about the properties of operating environment [78]. To address this issue, different authors have applied passivity theory to design controllers commonly known as passivity based controllers [101], [102], [79]. Passive systems are class of dynamic systems whose total energy is less than or equal to the sum of its initial energy and any external energy supplied to it during interaction. Hence passivity based controller design ensures a bounded energy content and the system achieves equilibrium at its minimum energy state. Any energetic interconnection of two passive systems wont affect the passivity of the combined system. As a result an interconnection of a passivity based controller, a passive manipulator and a typical unstructured operating environment which is often passive results in an overall passive system whose Lyapunov stability is always guaranteed. Passive controller designs for domestic robot manipulators have been often addressed together with interaction control in a unified scheme to achieve a compliant, asymptotically stable and robust manipulator [79], [103], [104].

Safety aware control schemes that incorporate safety metrics in controller design were also proposed in literature. Focusing on collision risks to a human user, these controllers utilize a given safety metric to detect possible unsafe situations and use the controller to ensure acceptable safety levels defined in the metrics are achieved in order to avoid possible injuries. Using impact potential as a safety metric, [47] proposed an impact potential controller for a multiple DOF manipulator. In this hierarchical controller design approach, the resulting safety status of a high level motion controller torque output is evaluated according to the metric by a protective layer controller and clipped to an acceptable level in case of possible unsafe condition. By using energy levels that cause failure of the cranial and spinal bones as a safety criteria, authors in [105] propose an energy regulation control that modifies desired trajectory of the controller to limit overall energy of a manipulator. After analysing soft tissue injuries and their relation with robot parameters, [60] proposed a velocity shaping scheme that ensures possible sharp contact with a multiple DOF rigid robot wont result unacceptable injury to a human user.

Controller design can also increase post-collision safety by including collision detection and reaction strategy. By using model based analysis, authors in [106] defined energy based collision detection signal by using disturbance observer and identified a number of reaction strategies to both stiff and compliant robots.

## V. Conclusion

The previous sections presented different safety metrics and safety related issues in mechanical design, actuation and controller design of domestic robots. Though mechanical and controller subsystems are treated separately in this paper, it is important to note that safety also depends on the interaction between components making up the complete robot. For example, a failure in the sensory unit is a risk not only in the sensing aspect but also has consequences in the motion planning or control. Such propagation of risks is essential and must be detailed in the risk assessment level of the safety analysis.

Continuous improvements in risk elimination or reduction designs are not possible without suitable safety metrics that can be used for validation. These metrics are needed not only for collision but also other feasible risks in domestic robotics. A number of collision focused safety metrics for domestic robots were discussed in this paper and an experimental comparison of these metrics that follows a standardized testing procedure is essential to define a universally acceptable safety metrics for collision risks in domestic robotics. A groundwork towards a standardized safety evaluation of domestic robots for collision risks was performed at crash test facility in [107], [108].

Light weight and compliant manipulators are mechanical designs of choice in domestic robotics. Ongoing researches on mechanical design and actuation to achieve better performing domestic robots should ensure that safety requirements are not violated as well. Control systems should also keep up with mechanical design and actuation advancements to guarantee stability and provide acceptable manipulation capability.

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